ORIGINAL ARTICLE

A Dynamic and Direct Visualization Model for the Study of Nasal Airflow

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Objective: To evaluate nasal airflow characteristics during physiologic breathing in normal and pathologic conditions.

Design: The choana of an anatomical human model was connected to a pump that simulated physiological pressure changes in the upper airway system. Normal ambient air was used as medium. The airstream was marked with aerosolized water particles, and was observed through an exact but translucent replica of the original nasal septum.

Results: In physiologic conditions the airflow is mixed. Turbulence is clearly visible even with low flow velocities. There is less turbulence with lower flow rates. The nasal airflow follows a triphasic pattern of acceleration, near–steady state, and deceleration. Turbulence is prominent in the first and third phases. The main flow stream passes through the middle meatus at all rates. Hypertrophic mucosal membranes and turbinates increase the proportion of air passing the middle meatus. With decongested turbinates, flow distribution is more even. After turbinectomy there is a significant amount of airflow passing along the floor of the nose. The olfactory region is aerated only toward the end of inspiration and during the entire expiration phase.

Conclusions: This model allows the investigation of airflow distribution and turbulence under physiologic conditions and the examination of the influence of pathologic conditions on these parameters. Overzealous trimming of turbinates results in an unphysiologic distribution of airflow.

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THE NASAL airway passages are responsible for 3 major functions: transport of adequate amounts of air, optimal conditioning of the inspired air, and olfaction. The extension of the inferior and middle turbinates and the septum create a large surface area, which, lined by mucosa, provides a ciliated, moist surface in contact with the inspired air. This maximizes both olfaction and the ability to climatize the inspired air by heating, humidifying, and filtration. Perhaps of equal importance for an optimized nasal function are the dynamics of the airflow. Teleologically, the ideal airflow in the relaxed state would appear to be a turbulent flow to increase mixing and contact of particulate matter with the mucosal surface. During physical exertion, however, laminar airflow with its smaller resistance would be optimal to minimize the work of breathing and ensure adequate oxygenation and ventilation. It is still unclear whether in vivo nasal airflow is turbulent or laminar under physiologic conditions.

The objectives of this study were to examine the nasal airflow patterns in a human nose and to examine the influence of structural changes of the turbinates and nasal septum.

RESULTS

Distributions of airflow patterns were clearly visible. Turbulent airflow patterns can be readily distinguished on the videotapes by irregular distribution of the otherwise streamline flow.

Inspiration begins with a short phase of acceleration, which is followed by a longer near–steady state phase, and ends with a relatively short period of deceleration.

Expiration, however, is characterized by much shorter periods of both acceleration and deceleration. Since the pump simulated the physiologic respiratory apparatus of an adult human, this time pattern of airflow can be expected to be present also in the healthy human nose and is not primarily a consequence of the pump system's setup.

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MATERIALS AND METHODS

A formalin-fixed 55-year-old male cadaver head with no nasal abnormality was sectioned in the midsagittal plane. The nasal septum was removed en bloc, and from this a transparent replica was created with Plexiglas and epoxypolyester resin. This "neoseptum" replaced the original septum, creating an anatomically correct viewing chamber of the heminose. The chamber was connected in an airtight fashion to a piston pump, as described elsewhere,[1] with which the dynamic physiologic respiration could be simulated. Water particles were aerosolized (diameter, 0.5-5 µm) by an ultrasonic generator to make the airstream visible. This reservoir was placed anterior to the naris for inspiration (**Figure 1**). To further improve visualization of the airstream, the lateral nasal wall was tinted black.

The nasal chamber without modifications of the turbinates or "neoseptum" was designated as the "decongested state" for analysis. To simulate normal and pathologic states, a modeling paste (Araldite epoxy systems 427; Ciba, Basel, Switzerland) was used to enlarge the nasal turbinates or create a septal spur. The inferior turbinate was finally partially resected to study the effect of a turbinectomy. Thus, settings for decongested, normal, and congested mucosa, as well as for the condition after turbinectomy and with a significant septal spur were obtained. Airflow was studied at 3 different flow rates: 10 L/min, 23 L/min, and 35 L/min.

The airflow was recorded with photographs and a videotape recorder.

The route of the airflow as a function of time, presence of visible turbulence, and timing of gas exchange were evaluated. Turbulence was defined as irregular streamline patterns and formation of visible eddies on direct observation or slow-motion video analysis.

DECONGESTED NASAL MUCOSA (UNCHANGED CADAVER)

Figure 2 illustrates streamline patterns as observed on real-time and video analysis in the decongested mucosal state. At a flow rate of 10 L/min, the inspired airflow accelerates during the initial 0.6 seconds. A near–steady state is reached at this point and is continued for 1.3 seconds. The deceleration starts 1.9 seconds after the onset of inspiration and ends after another 1.1 seconds (duration of inspiration totals 3 seconds). The duration of the expiration is 2 seconds. The acceleration and deceleration during expiration are less prominent. After 5 seconds the next inspiratory cycle starts again.

The air fills the valve region of the nose during the early acceleration phase in an irregular pattern. As soon as a steady state is reached, most of the flux passes over the head of the inferior and middle turbinates with the main stream passing through the middle meatus (Figure 2, D, and **Figure 3**, A). A smaller portion of the airstream passes along the floor of the nose. No streamlines are visible in the olfactory region. During deceleration, the olfactory region is filled totally with air (Figure 2, E, and Figure 3, B). In contrast to these well-defined patterns, airflow during expiration is much more evenly distributed within the nasal cavity (Figure 2, G).

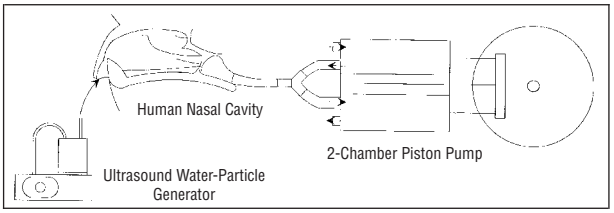

Figure 1. *Experimental setup. Schematic equipment diagram for dynamic airflow observation.*

Turbulent airflow is seen during the entire steady state phase. An eddy is formed in the anterior half of the inferior meatus, creating much turbulence in the posterior parts along the floor of the nose. Another area of high turbulence is in front of the head of the middle turbinate. During acceleration and deceleration, turbulence is much less prominent. During expiration, most turbulence is seen in the upper region of the nose.

This evaluation was repeated with flow rates of 23 L/min (383 mL/s) and 35 L/min (583 mL/s). With increasing flow volume and therefore flow velocity, the acceleration/deceleration phases are shorter and near–steady state is reached sooner. Thus, the near–steady state dominates. Flow distribution patterns do not change. But increasing the flow rate produces a more even distribution of the streamlines, with more air going through the upper and lower meatus. With increasing flow rate there is more turbulence. Turbulence starts in the entrance to the middle meatus.

NORMAL NASAL MUCOSA (AUGMENTED TURBINATES)

Figure 4 illustrates streamline patterns as observed on real-time and video analysis in the normal mucosal state. Airflow accelerated during 0.6 seconds. The duration of the near–steady state is 1.3 seconds. Deceleration takes 1.1 seconds and expiration 2 seconds. The duration of the phases does not change, since the flow volume per second remains constant and only the diameter of the airway changes.

Basically, the observed patterns are the same as described above. The filling of the preconchal region is limited to the entrance to the middle meatus (Figure 4, A). The streamlining of the flow is markedly more prominent. The main flux passes the middle meatus through its entire length, and very little air is passing along the nasal floor (Figure 4, D, and **Figure 5**, A). A very faint streamline can be seen passing over the head of the middle turbinate, joining the main portion in the middle meatus further back. During expiration, the main flux passes through the inferior half of the nose (Figure 4, G).

Turbulence is visible in the main airstream (ie, the middle meatus). The turbulence-induced irregularities begin at the level of the head of the middle turbinate.

This evaluation was repeated with flow rates of 23 L/min (383 mL/s) and 35 L/min (583 mL/s) (Figure 5, B).

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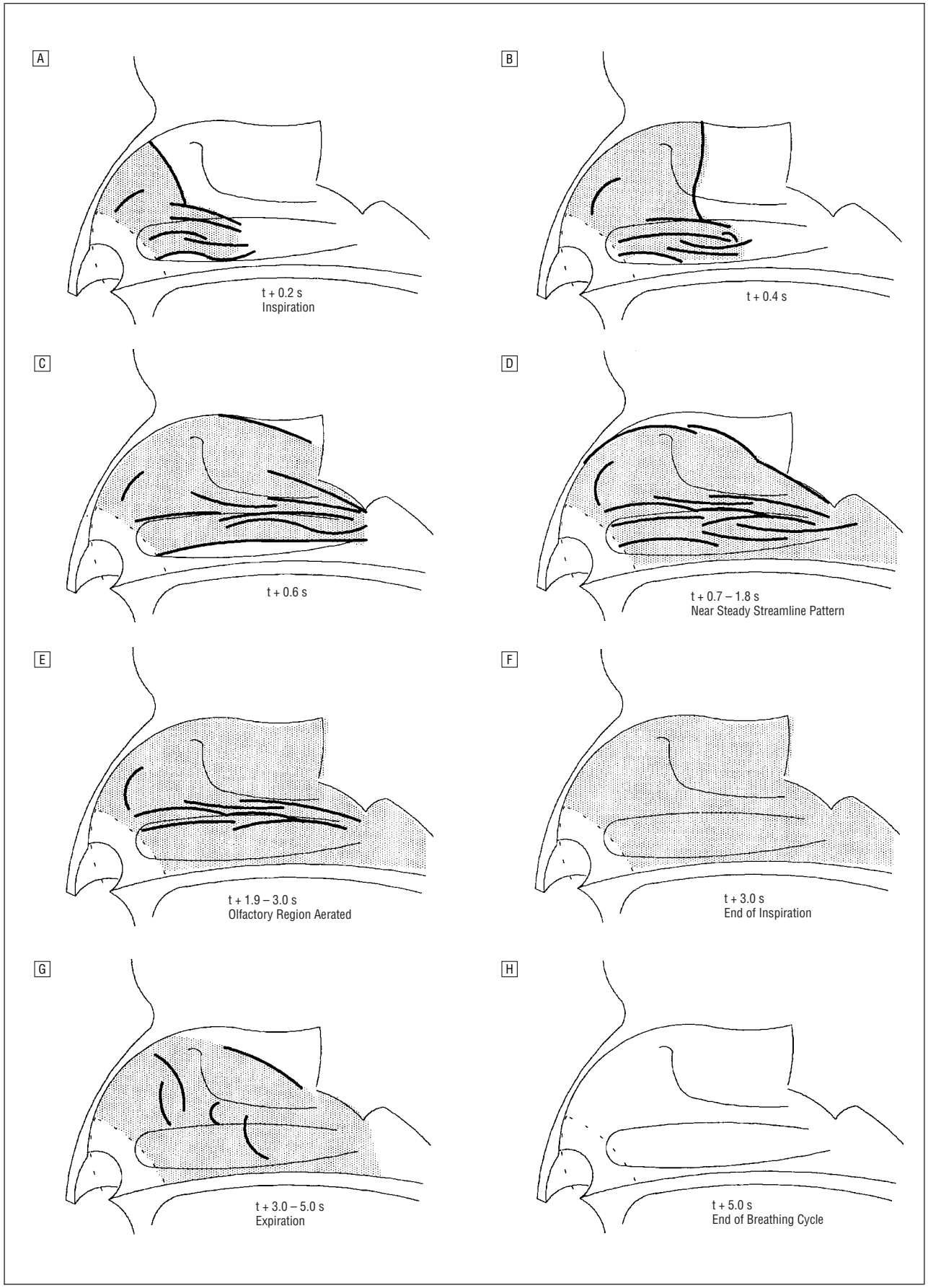

Figure 2. *Schematic drawings of streamline patterns as observed on real-time and video analysis in the decongested mucosal state. Flow = 10 L/min (167 mL/s).*

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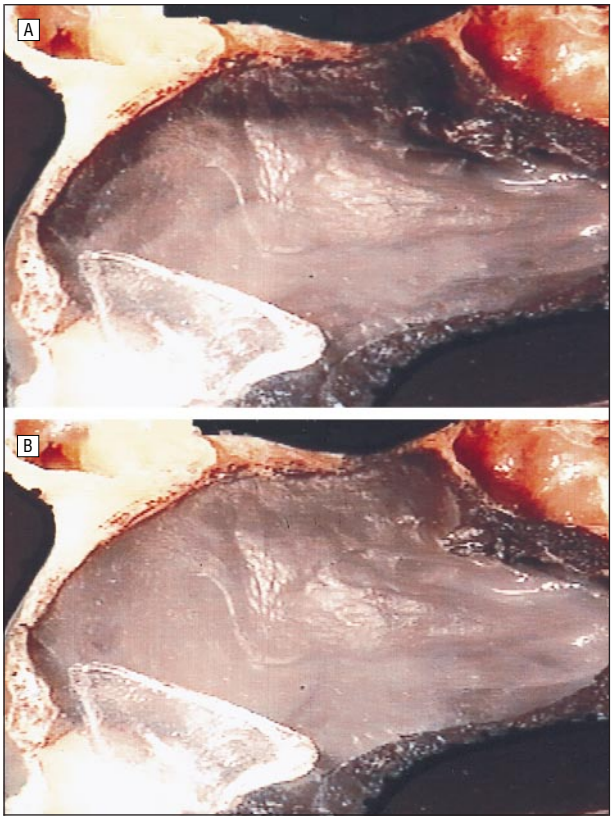

Figure 3. *Videoprint taken during inspiration in a decongested nose. Near–steady state streamline pattern (A) and olfactory region aerated during end of inspiration (B).*

Again, the acceleration/deceleration phases are shorter and near–steady state is reached sooner. Thus, the near–steady state dominates.

Flow patterns do not change. But increasing the flow rate produces a more even distribution of the streamlines, with more air going through the upper and lower meatus. With increasing flow rate there is more turbulence. Turbulence starts in the entrance to the middle meatus.

HYPERTROPHIC TURBINATES (FURTHER AUGMENTED TURBINATES)

The differences found between the model in its native and its augmented states become more pronounced. While the phases do not change, the streamline pattern is concentrated exclusively in the middle meatus. The observed velocity of air is higher than in the normal or decongested state. We observed fewer turbulences with lower flow rates.

SEPTAL SPUR

The phases do not differ from the situation described above. The flow patterns are almost identical with those of a normal nose for small and medium-sized spurs. The spur deflects the nasal airflow significantly toward the middle and inferior turbinates compared with the normal or decongested cavity. Due to the spur, more turbulences are visible, with an eddy behind the spur.

PARTIAL INFERIOR TURBINATE RESECTION

Phases do not change. The nasal airflow is concentrated along the floor of the nose and the lower septum areas, whereas the middle meatus shows fewer streamlines. Turbulences are visible and concentrate in the region of the inferior meatus.

COMMENT

MODEL

The ideal model for studying the airway would be a direct in vivo measurement, but the problem encountered in such studies is the small dimension and inaccessibility of the nasal airway in humans. Thus, any measuring instrument introduced into the airway will alter the flow pattern and interfere with the analysis. If measurement is undertaken indirectly, a series of assumptions are introduced into the analysis, which can result in inaccuracies or, even worse, in divergent results. With in vitro studies, on the other hand, it is difficult to reproduce the complex anatomy of the nasal cavity and its physical parameters such as humidity, elasticity, and highly variable topography. Numerical simulation models, for instance, are almost impossible without the assumption of a laminar flow and steady state conditions.[2-4]

To circumvent these problems, we developed a human cadaver model with a reconstructed nasal valve region. An intact and anatomically correct nasal valve is particularly important since this has been shown to be the flow-limiting segment in a normal nose.[3,5] By performing this study ex vivo, inaccuracies inherent in offsize fabricated models and corrective calculations could be avoided.[2,6-8] Another major advantage of our model was the use of a physiologic breathing cycle rather than the steady flow velocities used in previous studies. Furthermore, by connecting the pump to the pharyngeal side of the nose, the air was "inspired" through negative pressure in a physiologic manner from an immensely big reservoir, rather than being externally injected under positive pressure. Expiration was again simulated by a positive pressure, as is the case under physiologic conditions. In addition, this model used humidified air as the transport medium rather than an incompressible fluid, thus obviating the need for corrective mathematical calculations.[7] No devices or probes were present in the airstream and thus did not influence our results.[6,9] This analysis was thus based exclusively on direct observation and on analysis of the videotapes in slow motion. Hence, this experiment cannot yield numerical data concerning air speed, pressure, or other physical parameters. Observation is ideal for determining flow distribution and turbulence patterns, whereas velocities or pressure gradients can only be inferred.

In the end, there rests a choice between pure observation of an almost normal physiologic situation and refined measurements, the latter almost invariably implicating simplification of possibly important features. To us, it seems more appealing to closely watch a physiologic process with limited possibilities to produce

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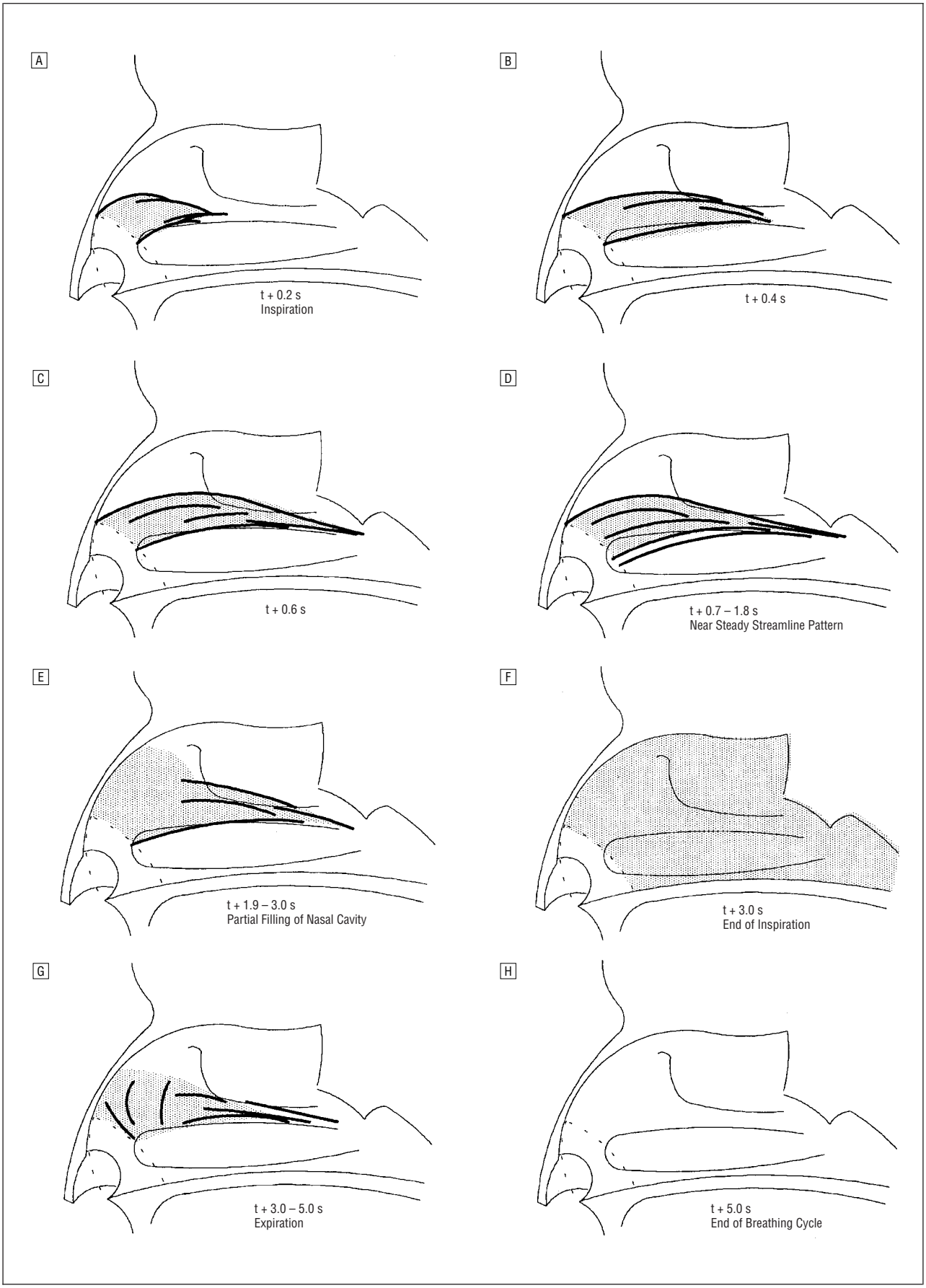

Figure 4. *Schematic drawings of streamline patterns as observed in real-time and video analysis in the normal nasal mucosal state. Flow = 10 L/min (167 mL/s).*

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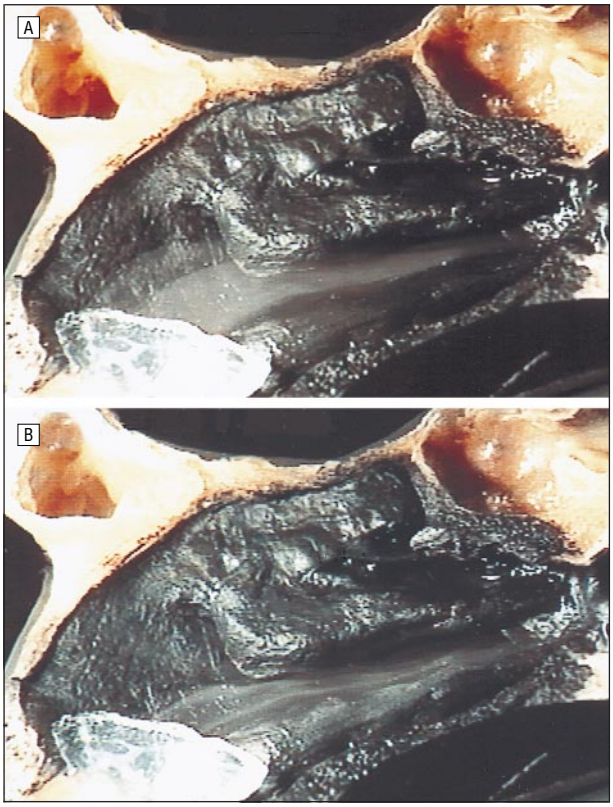

Figure 5. *Videoprints taken during inspiration in a normal nose at a flow rate of 10 L/min (A) and 23 L/min (B).*

numerical output than attempt to produce very accurate numerical data of a process going on under quite unphysiologic conditions.

TURBULENT VS LAMINAR FLOW

In this model, a partially turbulent flow was observed even at low air velocities in most parts of the nasal cavity. This finding is supported by results of other studies.[3,6,7,9-12] The amount of turbulence increased with higher air velocities, substantiating the results of most previous investigations. The onset of turbulence occurs in the valve region (ie, head of the inferior turbinate, septum, upper lateral cartilage), as documented by other groups.[3,6,7,10-12] This underscores the well-known clinical importance of these structures. From a physiological perspective, a turbulent flow would seem sensible, since it enhances contact between air and the mucosal layer. By doing so, humidification, cleaning, and warming are optimized. Other investigators[2,13] have found a predominantly laminar flow, particularly at rest. The majority of these investigations were computer-aided numerical simulations, however.[2,4,13] The assumption of laminar flow was a necessary part of the premise in most of the computer-assisted simulation trials.

DISTRIBUTION OF AIRFLOW

There is conflicting evidence on the primary route of airflow through the nose, with a discrepancy between a group of trials undertaken with computer-aided simulations and a group of observation-based trials. In their computer-assisted simulation study, Elad et al[13] conclude that the flux of air tends to follow along the nasal floor. In a different numerical simulation, Keyhani and coworkers[2] found the highest axial velocities to occur along the floor of the cavity and a large portion of the volumetric flow to pass through this region. Schreck et al,[7] on the other hand, found results more similar to our observations in their work based on dyed water flowing through a Plexiglas model. Other studies also found the main stream of air to pass through the middle meatus.[8-11] By using xenon 133 gas, Hornung and colleagues[9] showed that most of the radioactivity could be detected in the middle region of the nose. In addition, they detected a different airflow pattern depending on the exact site of release of the labeled gas, with medially released markers going along the inferior parts of the nose and laterally released markers being found more in the upper parts of the nose.[9] Arbour et al[12] found with laser anemometry half of the nasal airflow to pass the inferior half of the nose, which includes both the middle and the inferior meatus.

In our model, the main flow passes over the head of the inferior turbinate through the middle meatus. The distribution of the airflow is much more homogeneous in the decongested nose, whereas the percentage of air passing through the middle meatus becomes increasingly prominent in the congested nose, as demonstrated in the different manipulations of the model. Septal spurs of small size do not seem to significantly influence nasal aerodynamics when located dorsal to the nasal valve region. Changes in the air speed throughout the physiologic range lead only to minor variation of the flow profile.[6-8]

OLFACTION

The olfactory region of the nose is ventilated toward the end of inspiration, when air speed declines significantly, causing turbulence in the olfactory region. During expiration the distribution of flow is much more even and the olfactory region is aerated early in and throughout the breathing cycle. Thus, we can confirm the finding of Schreck et al[7] that the olfactory membrane is not directly exposed to the high-velocity airstream during inspiration but rather to a much weaker "secondary flow," prolonging contact time of olfactory active particles with the sensing organ.

CLINICAL IMPLICATIONS

There are a number of clinical conclusions that may be drawn from this study.

1. This study confirms that functional endoscopic sinus surgery should affect the nasal airflow pattern because the arched main stream of airflow passes the middle meatus, the primary target of all procedures in functional endoscopic sinus surgery. Therefore, a significant improvement in nasal breathing can potentially be achieved by functional endoscopic sinus surgery, especially in narrow and congested noses.

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2. The anterior aspect of the middle turbinate lies in the middle of the main airstream and thus protects the ethmoidal infundibulum from excessive drying and crusting. For this reason we advocate preservation of the middle turbinate whenever possible, and only the lateral aspect of a concha bullosa should be resected to preserve function.

3. The improvement in chronic sinusitis attained by widening this key area may be due to better air-mucosa contact, which may in turn have a positive influence on the mucociliary clearance and transport mechanisms.

4. In a congested narrow nose, a partial inferior turbinectomy offers a significant improvement in total nasal airflow resistance. After turbinate surgery, there is more airflow along the nasal floor with higher velocities. However, with excessive surgery there can be mucosal drying and crusting. Therefore a conservative technique is indicated, particularly at the nasal valve region (head of the inferior turbinate).

5. A septal spur in a "normal" nose does not affect airflow pattern significantly, and hence there are limited indications for its resection. However, even a moderate spur in combination with other nasal abnormalities (eg, mucosal swelling) can be a significant cause of altered nasal function, and thus becomes an indication for corrective surgery.

6. In general, the location of a pathologic condition can be of more importance than its magnitude, particularly when the flow-limiting region of the nose, ie, the nasal valve region, is affected.

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